PHYSICS

Harnessing chirality for valleytronics

Artificial magnetic fields bend electron trajectories in gapped graphene

By Mark B. Lundeberg[1] and Joshua A. Folk[2]

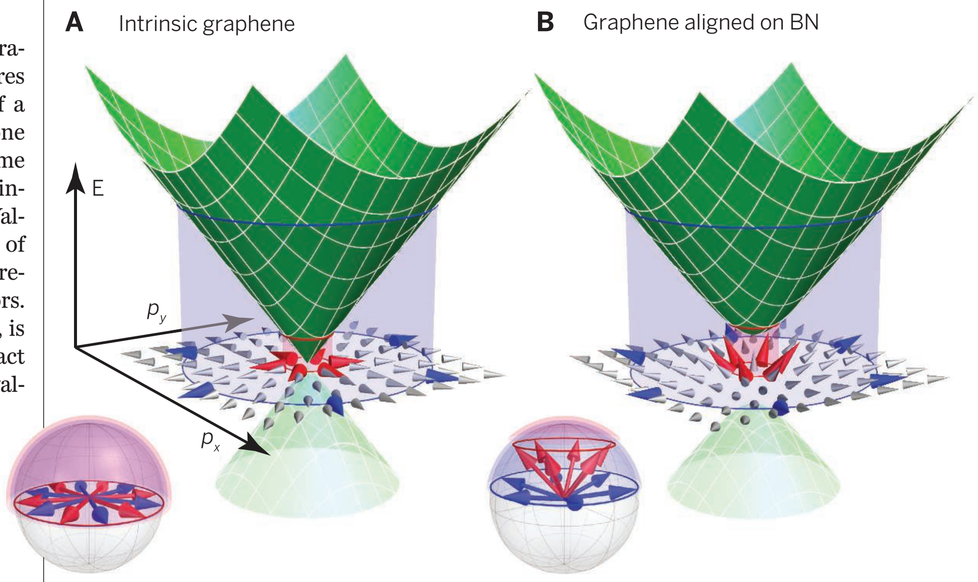
One of the unusual electronic characteristics of graphene is that the direction of motion of its charge carriers is locked to an extra quantum mechanical degree of freedom, known as pseudospin. Graphene is in this way similar to the conducting surface layer of a topological insulator, where the direction of motion of the carriers is locked to their true spin—that is, to their magnetic moment. Whereas the true spin state of an electron can be described as a superposition of spin-up and spin-down components, pseudospin in graphene is a superposition of electron orbitals of the two carbon atoms in a hexagonal lattice unit cell. To date, graphene's pseudospin has played only a subtle role in carrier scattering, and in phenomena that are directly sensitive to the phase of a quantum mechanical wave function. On page 448 of this issue, Gorbachev *et al.* (*1*) show that pseudospin, modified in the right way, can be used to drive a so-called valley current in a graphene device. That is, a voltage applied across the device gives rise to counterpropagating streams of carriers in graphene's two band structure valleys. By harnessing its built-in chirality, an all-electrical valleytronic circuit using graphene is demonstrated.

Valleytronics is the name given to a paradigm for information processing that stores information in the crystal momentum of a carrier—that is, in its freedom to exist in one band structure valley or another. The name draws an analogy to spintronics, where information is stored in the carrier spin. Valleytronics may offer lower dissipation of energy for classical circuits, as well as reduced decoherence in quantum processors. A roadblock to practical circuits, however, is that charge carriers in most materials react to external fields independently of their valley, thereby preventing the efficient generation and detection of valley currents.

The experiment reported by Gorbachev *et al.* removes the symmetry between the two valleys in graphene by giving each a different pseudospin texture. These valleys, labeled *K* and *K′*, appear as inverted Dirac cones in the band structure (see the figure). Precisely aligned boron nitride (BN) substrates are used to bend the pseudospin up out of the plane of the momentum at the tip of the *K* valley and down out of the plane at the tip of the *K′* valley. Electrons in the modified valley tips are driven perpendicular to applied electric fields, left or right depending on their valley. This valley Hall effect is analogous to the ordinary Hall effect, where transverse voltages are generated by charge currents in a magnetic field. But the valley Hall effect does not require a magnetic field. Instead it relies on nontrivial pseudospin texture within each valley, similar to spin-orbit–based anomalous or spin Hall effects (*2*–*4*). The valley Hall effect was first observed via an identical pseudospin-based mechanism in molybdenum disulfide (MoS_2) (*5*).

The relation of the valley Hall effect to pseudospin is easier to understand by comparison with quantum and classical effects of a magnetic field. The vector potential associated with a magnetic field adds phase (Aharonov-Bohm or AB phase) into the wave function of a charge moving along the vector potential lines. Interference of different AB phases for slightly different paths provides a quantum explanation of the classical Lorentz force on a moving charge, which ultimately depends only on the local magnetic field. Vector potentials can be finite even in regions where the field is zero, as in the space surrounding a long solenoid, so the AB phase and Lorentz force do not need to go together. For example, a particle traveling in a loop around a solenoid experiences no Lorentz force but accumulates an AB phase set by the amount of magnetic flux in the solenoid and independent of the path itself.

The present experiment is understood in terms of an analogous kind of quantum mechanical phase, known as Berry's phase, involving paths through momentum space (following the band structure) rather than through real space. Carriers in graphene accumulate a Berry's phase of 180° for a momentum-space circumnavigation of either valley, due to the 360° rotation of pseudospin locked to momentum. This situation resembles the AB phase from a path in the field-free region around a solenoid, in that the amount of phase is independent of details of the path; it is visible to experiment only through subtle signatures such as modifications to the quantum Hall effect. The Berry's phase does not alter the motion of charge carriers because the Berry's flux core



Into the valley. (**A** and **B**) The tips of graphene's Dirac cones are modified by an aligned boron nitride (BN) substrate. A small energy gap is introduced, and the pseudospin vectors (shown here for upper Dirac cone, *K* valley) are tilted out of the plane on BN. Blue circles show paths in momentum space circumnavigating the Dirac cone for larger magnitudes of momentum; red circles show these paths for smaller magnitudes of momentum. (Insets) Pseudospin vectors along blue and red paths trace out identical solid angles on a Bloch sphere for the intrinsic case (A) but different solid angles, leading to different Berry's phases, for graphene on BN (B).

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is locked inside a topological singularity at the tip of the cone.

For graphene-on-BN, the tips of the Dirac cones are rounded, and the pseudospin is tilted out of the graphene plane but is still locked to momentum. As a result, the pseudospin traces out a smaller solid angle (a smaller Berry's phase is accumulated) when circumnavigating the cone close to the tip. It is as if there were a Berry's flux spread across the tip of the Dirac cone, so larger circles in momentum space accumulate more Berry's phase. Carriers accelerated through this region of Berry's flux then experience direct classical effects, analogous to the Lorentz force for a charge moving through regions with magnetic flux. The acceleration leads to a transverse velocity that is opposite for the two valleys, spatially separating K and K' carriers.

The experiment can also be viewed from the point of view of conservation laws. Although pseudospin is often thought of as an abstract quantity, it is believed that the pseudospin vector itself encodes a (valley-dependent) angular momentum that, together with orbital angular momentum, must be conserved (*6*). For graphene-on-BN, accelerating a carrier from the bottom of the Dirac cone (pseudospin up or down) to the sides (pseudospin in the plane) requires a transfer of angular momentum that can only be accomplished by a shift transverse to the direction of acceleration. This experiment thus offers a real physical connection to the pseudospin in graphene.

Gorbachev *et al.* make two important steps toward practical valleytronics. Theirs is the first demonstration of valley current generation and detection by purely electrical means, in a material that is well suited to electronics (stable in air, easy to contact, offering high mobilities). Moreover, the valley degree of freedom is usually invisible to experiment in graphene—an advantage from the point of view of quantum coherence. The authors have created a tiny region in the band structure, accessed by small changes in gate voltage, where the valley influence is profound. This offers promise for a device in which valley freedom can be long-lived but still controlled electrically on a fast time scale.

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PLANT SCIENCE

Sex and the single fern

Separation of the synthesis and sensing of a signaling molecule controls sex in ferns

By **Tai-ping Sun**

Unlike animals, plants have two alternating generations: a diploid sporophyte and a haploid gametophyte. Through meiosis, the sporophyte produces haploid spores, which then give rise to gametophytes, a multicellular haploid structure that produces gametes for sexual reproduction. All seed plants and some non–seed plants are heterosporous, producing spores of different sizes: large female spores and small male spores. Most ferns, on the other hand, are homosporous; they produce a single type of spore. After germination, each fern spore has the potential to develop into a male, female, or hermaphrodite gametophyte. The developmental decision that determines the sex of a particular gametophyte depends on an interplant communication system mediated by chemical signals, termed antheridiogens (*1*, *2*). On page 469 of this issue, Tanaka *et al.* (*3*) show that an antheridiogen in the Japanese climbing fern (*Lygodium japonicum*) functions as more than a simple chemical signal. Covalent modification of the antheridiogen is required to trigger the fern's response to form male gametophytes. Temporal and spatial separation of the biosynthetic pathway between the early- and late-maturing gametophytes ensures the production of the antheridiogen, and the active male-inducing chemically modified form, at just the right time and place.

In a fern population, the early-maturing gametophytes (from spores that germinated first) produce and secrete into the aqueous environment antheridiogens, which promote differentiation of the neighboring younger gametophytes into males. These early-maturing antheridiogen-producing gametophytes will mainly develop the egg-forming female sex organ. This mechanism results in a small number of female gametophytes being surrounded by male gametophytes, promoting out-crossing and the maintenance of genetic diversity. Although this phenomenon was first discovered in 1950 (*4*), very little is known about how antheridiogen production is regulated and how this signal is perceived.

Tanaka *et al.* (*3*) show that an antheridiogen gibberellin (GA) A$_9$ methyl ester (GA$_9$-Me) is C3 hydroxylated and de-methylated to become an active GA (GA$_4$). This antheridiogen is produced via the conserved gibberellin biosynthetic pathway in plants (*3*, *5*, *6*), although the methyl transferase and methyl esterase for the conversion between GA$_9$ and GA$_9$-Me have not yet been identified. Importantly, Tanaka *et al.* find that genes encoding several enzymes for the production of GA$_9$ are more highly expressed in the early-maturing gametophyte than in the late-maturing young gametophytes. In contrast, the gene encoding the enzyme (GA 3-oxidase) for the conversion of GA$_9$ to the active GA$_4$ is preferentially expressed in the late-maturing young gametophytes, which are known to be highly sensitive to antheridiogens. This gene expression partitioning explains why only the early-maturing gametophytes produce the antheridiogen GA$_9$-Me and only the late-maturing younger gametophytes can respond to this pheromone to become males (see the figure).

In seed plants, GA$_4$ is an active hormone that plays a key role in regulating both vegetative and reproductive development (*5*, *6*). However, GA$_9$-Me is inactive. GA$_4$ turns on the GA signaling pathway by activating its nu-

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